

Investigation of Near-Axial Interference Effects

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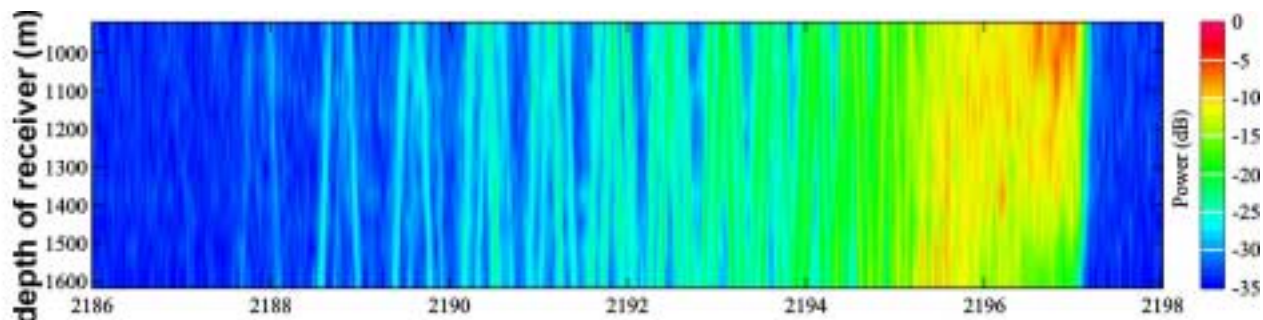
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LONG-TERM GOAL

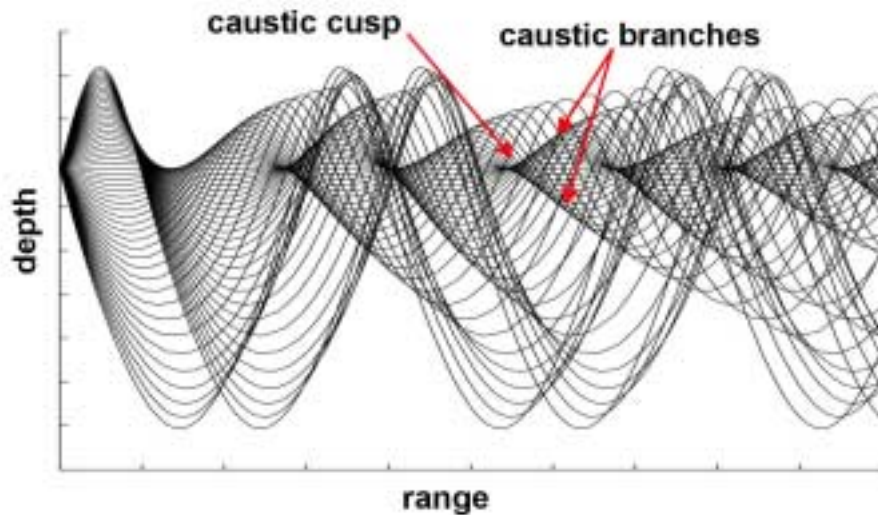
The long-term goal of this effort is to provide an improved way of interpreting the experimentally observed time-of-arrival patterns in long-range, low-frequency propagation in the deep ocean.

In many long-range propagation studies the source and receiver are placed close to the depth of the waveguide (SOFAR) axis to minimize the interaction of the acoustic field with the ocean's surface and bottom. The most pronounced characteristics of the time-of-arrival patterns for these experiments are early geometric-like arrivals followed by a crescendo of energy that propagates along the axis. In the following figure these characteristics are clearly shown for a time-of-arrival pattern measured during the AET experiment. This figure was adapted (with permission) from one published in Ref. (1).



The attempts that have been made to explain this late-arriving energy using geometrical acoustics have all failed. While the eikonal equation can be solved for the ray paths and travel times can be calculated by integrating along the ray paths, it is impossible to use geometrical acoustics to describe the propagation of energy along the waveguide axis because of the presence of caustics.

For ducted propagation in a waveguide there exist cusp caustics repeatedly along the axis. The following figure illustrates this pattern of caustics. It is a ray tracing for a source on the axis (and for relatively short ranges).



In neighborhoods of these cusp caustics there exists a complicated interference pattern. It is well known that a description in terms of geometrical acoustics is not valid in these neighborhoods because such a description presupposes that the waves associated with individual ray paths do not interfere with one another. These neighborhoods of interference grow with range and at extremely long ranges can even overlap. By their study we hope to provide a new understanding of the nature of the late-arriving energy in these propagation experiments.

OBJECTIVES

The primary objective of the visit sponsored by VSP was to develop a joint Naval International Cooperative Opportunities in Science and Technology Program (NICOP) proposal. We will request that the US sponsor for the NICOP proposal be Dr. Jeffrey Simmen, Ocean Acoustics Team Leader, ONR Sensing and Systems Division, Code 321OA. All the essential work needed to produce the proposal was completed. This included not only the preparation of routine items such as a curriculum vitae for each partner, a budget with narrative, and a bibliography; but also the determination of detailed objectives and approaches for the work that we briefly describe below.

The overall goal of the research to be proposed to NICOP is to provide a better understanding of the interference effects that are present for wave propagation in a ducted waveguide when the source and receiver are located near or on the axis of the duct. The primary application of this work will be the interpretation of time-of-arrival patterns observed in long-range acoustic propagation experiments in the ocean.

There are two standard field representations used to describe ducted propagation problems. First, a modal description in which the field is represented in terms of a finite number of propagating modes and an infinite number of evanescent or decaying modes. This representation is not particularly useful for describing the acoustic propagation experiments because the early arrivals are clearly best described using a ray picture and it is not always easy to generalize this representation to a range-dependent

medium. The second representation is in terms of geometrical acoustics. As we have mentioned this representation has not been found particularly useful for describing the late-arriving energy that propagates along the waveguide axis.

There is a third representation developed by Buldyrev and others (Refs. (2)-(4)) that addresses the problem of the interference of near-axial waves. Buldyrev showed that the interference of the wave fields that correspond to near-axial rays, and is associated with the cusp caustics, leads to a coherent structure that propagates along the axis like a wave. In regions removed from the caustics where geometrical acoustics can be considered valid, this structure, called the “axial wave” reduces to the simple wave associated with the ray path that propagates along the axis of the waveguide.

In Buldyrev’s representation the total field is given in terms of three contributions; the axial wave, a sum of terms that in the asymptotic or high-frequency limit correspond to the ray-like arrivals having early travel times that are observed in the experiments, and a third term that represents the energy that left the source at high launch angles. The value for the launch angle that distinguishes between the latter two contributions is somewhat arbitrary and in practice would depend on the application. In the asymptotic limit the last contribution represents an infinity of ray-like arrivals having large launch angles. It may be particularly important for those types of short-range propagation problems where the decaying modes provide a significant contribution to the field.

Our goal is to apply Buldyrev’s representation to the long-range propagation experiments. The hope is that by doing so we will provide an improved way of interpreting the experimentally observed time-of-arrival patterns.

APPROACH

This work represents a collaboration between N. S. Grigorieva and G. M. Fridman at the St. Petersburg State University of Ocean Technology and D. R. Palmer at NOAA/AOML in Miami. Professor Grigorieva will be responsible for summarizing and interpreting the Russian work upon which the collaboration is based, analytic analysis, and will work with Dr. Fridman who will be responsible for numerical calculations. Dr. Palmer will be responsible for interpreting the relevant long-range propagation experiments, interfacing with U.S. researchers working on the same general problem, and will work with Prof. Grigorieva on analytic problems. The members of the team are productive, highly-motivated researchers who bring to the project complementary qualifications and experience well matched to the work to be undertaken.

The work has been divided up into three different phases:

1. Provide a summary of the body of work done in Russia by V. S. Buldyrev and associates on the representation of near-axial wave fields. This work is the basis for the present investigation. For the most part it is not available in English.
2. Describe the general approach using the simplest model that possesses the essential characteristics of the problem; namely, the existence of cusp caustics along the sound channel axis. This model consists of an infinite layered medium for which the square of the index of refraction is quadratic in the depth variable. This model, which we call the “reference model” is ideal for this purpose because it is

well known. While the reference model is simple, it can be used to characterize the essential characteristics of the problem as well as to determine the numerical and analytic techniques required for consideration of the case where the index of refraction has a more complicated coordinate dependence.

3. Generalize the ocean model in a two-step process. The first step will be to use a sound speed profile that possesses a realistic depth dependence. The second step will then be the inclusion of range-dependence. While the first step could be done using, e.g., a WKB approximation, we will instead base the analysis on the approach developed in Refs. (2) and (3). In this approach coordinate variables used are natural ones for describing the field close to a waveguide axis and the axial-wave portion of the field is represented using an integral representation. This method will also be used for the second step since it is general enough to include range dependence in the sound speed.

Much of the essential preliminary work outlined in (1) and (2) has already been done. A draft manuscript, based on the idealized ocean model, is in the final stages of preparation.

TRAVEL COMPLETED

Table 1. Summary of visits conducted under this VSP.

Person Visited	Position	Institution / Conference	Location	Scientific Purpose	Dates
Kristina B. Katsaros	Laboratory Director	NOAA/AOML	4301 Rickenbacker Cswy., Miami, FL 33149	Laboratory Orientation	01/22/01
Frederick D. Tappert	Professor	RSMAS/Univ. of Miami	4600 Rickenbacker Cswy., Miami, FL 33149	Scientific discussions, Tour of facilities	01/22/01 01/23/01 01/25/01 01/29/01
Michael G. Brown	Professor, Dept. Chairman	RSMAS/Univ. of Miami	4600 Rickenbacker Cswy., Miami, FL 33149	Scientific discussions	01/25/01 01/30/01
Ding Lee	Scientist	Yale Univ. (visiting Miami)	P.O. Box 208285, New Haven, CT 06520	Scientific discussions	01/28/01 01/29/01

RESULTS

1. We concluded that the research should not emphasis only the late-arriving energy in the experiments but, rather, the complete field including the high launch-angle energy that is often lost to bottom interactions in typical ocean acoustic propagation studies. This conclusion is based on the thought that the work may have application to other propagation problems.

2. We concluded the best approach to generalizing the sound speed model was to use the results in Refs. (2) and (3) rather than to use one based on WKB or the adiabatic mode approximation.

3. We concluded it is absolutely necessary to provide an English-language summary of Buldyrev's work.
4. We established professional relationships with U.S. researchers at the University of Miami involved in related work.

IMPACT/APPLICATIONS

This effort represents a new opportunity for collaboration between U.S. acousticians and Russian specialists in wave propagation. The so-called St. Petersburg school of diffraction and wave propagation, associated primarily with the names of Profs. Babic, Buldyrev, and Buslaev, and even earlier Prof. Fock, has developed asymptotic techniques that have had worldwide application to a host of applied problems. In addition, the researchers in St. Petersburg associated with this school did extensive work in underwater acoustics during the 1980's and earlier. While U.S. researchers in underwater acoustics have close, ongoing relationships with their colleagues at a number of Russian institutions, including those in Moscow and Nizhny Novgorod, no such collaboration exists between U.S. acousticians and members of this school of diffraction and wave propagation in St Petersburg.

The benefits that can come from such a collaboration are great. The present work represents a unique opportunity to apply theoretical research done by this school to pragmatic problems in underwater acoustics. For the first time Russian theoretical research not generally known in the U.S. will be used to help interpret U.S. long-range underwater acoustics experiments.

The benefits are not one-sided. If there is a weakness in the St. Petersburg school, it is that it is somewhat isolated from contact with those who apply its theoretical research. Russian researchers will have an opportunity to learn some of the practical aspects of recent, exciting, sound propagation experiments conducted under Navy auspices.

TRANSITIONS

A better understanding of the interference effects in long-range underwater acoustics experiments could not only provide new methods of exploiting these experiments for ocean acoustic remote sensing, including climate and nuclear explosion monitoring, but could also provide a basis for future, unanticipated, applications of low-frequency acoustics. New ocean remote sensing techniques have obvious societal benefit. The techniques to be developed and the knowledge to be gained has relevance to other fields including electromagnetic propagation in the atmosphere and wave propagation in elastic media.

RELATED PROJECTS

This work falls within the context of the ONR Ocean Acoustics Program (Code 321OA) S&T Thrust, Long-range Propagation. It complements the Code 321OA theoretical work having grant numbers N000149710046, N000140110313, N000149810540, N000149810079, N000149810899, and N000149710426 and experimental work on long-range propagation having grant number N000149710258.

REFERENCES

- (1) P. F. Worcester *et al.*, "A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean," *J. Acoust. Soc. Am.* **105**, 3185-3200 (1999).
- (2) V. S. Buldyrev, "Asymptotic behavior of solutions of the wave equations that are concentrated near the axis of a two-dimensional waveguide in an inhomogeneous medium," *Problemy Mat. Fiz.*, **3**, 5-30 (1968) (in Russian). [English translation: in *Spectral Theory, Topics in Mathematical Physics*, **3**, M. Sh. Birman, ed. (Consultants Bureau, New York, 1969), pp. 1-23].
- (3) V. S. Buldyrev, "The field of a point source in a waveguide," *Trudy Mat. Inst. Steklov*, **115**, 78-102 (1971) (in Russian).
- (4) V. S. Buldyrev, A. I. Lanin, and Z. A. Yanson, "Calculation of a field at the axis of a symmetric waveguide," *Voprosy Dynam. Teor.*, **14**, 84-93 (1974) (in Russian).